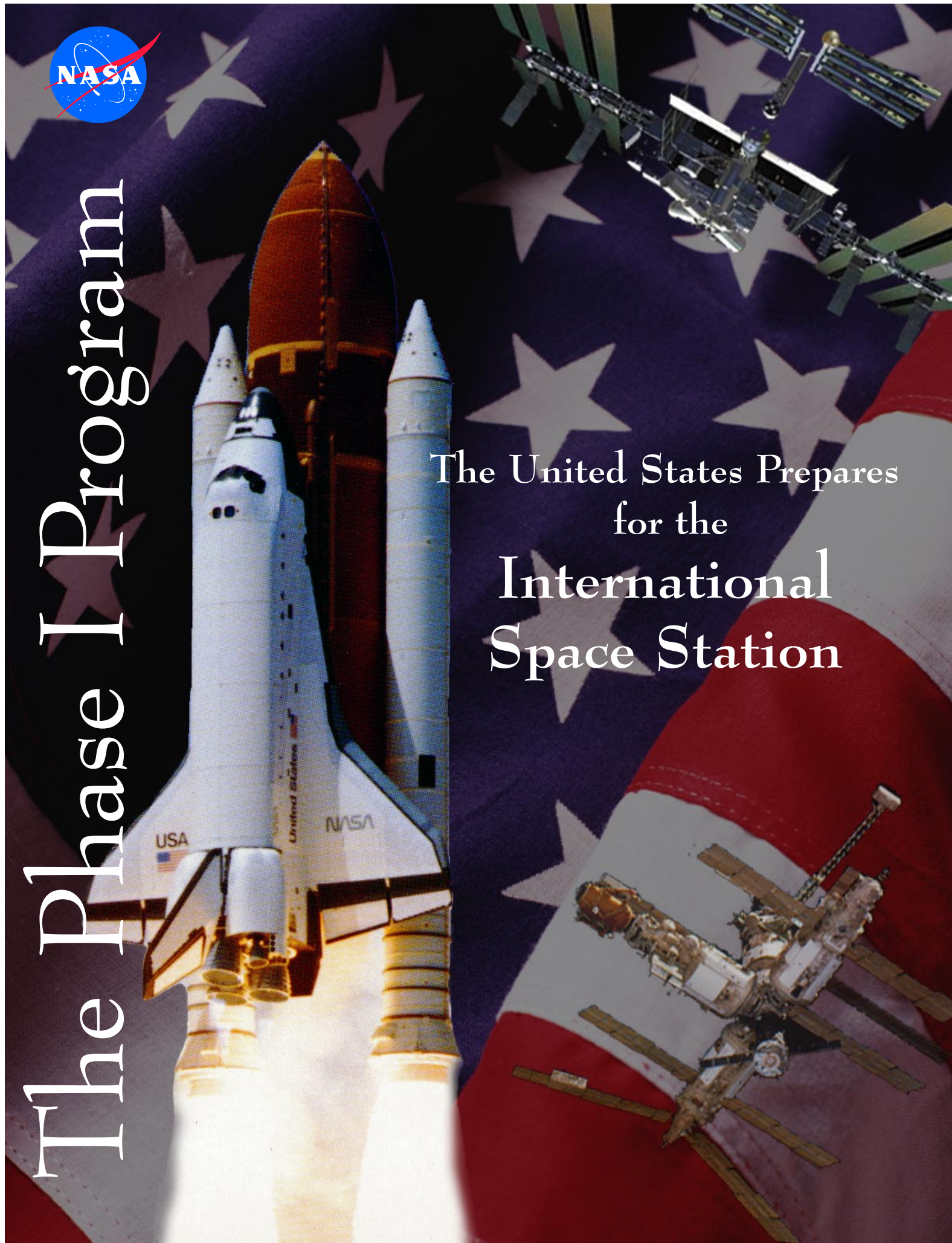


The Phase I Program

The United States Prepares
for the
International
Space Station



Foreword

The United States and the Soviet Union made history in 1975 as American and Soviet spacecraft docked together on orbit. Known as the “handshake in space,” the Apollo-Soyuz Test Project was the first step in the journey we now take together as friends two decades later.

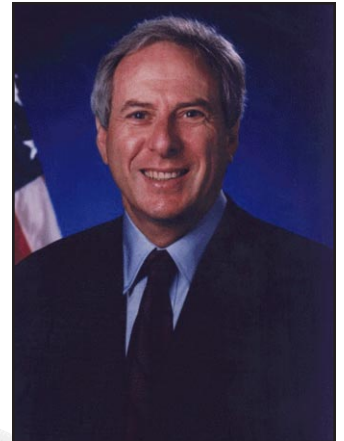
In 1992, U.S. President George Bush and Russian President Boris Yeltsin signed an agreement for peaceful cooperation in space. This resulted in plans to fly an American astronaut on the Russian space station *Mir* and two Russian cosmonauts on the Space Shuttle. In 1993, U.S. Vice President Albert Gore and Russian Prime Minister Victor Chernomyrdin announced the expansion of joint activities in human space flight. As a result, I signed an agreement to welcome Russia as an integral partner in the International Space Station (ISS) Program on November 1, 1993.

The inclusion of Russia as an ISS partner presented NASA with a singular opportunity. Russia entered the ISS partnership with a unique set of experiences and capabilities in long-duration human space flight. Taking advantage of this history, we initiated a three-phase, incremental development process for the ISS. Phase I of this process was designed to decrease the risks associated with assembling, operating, and conducting research on the ISS; it consisted of a series of Space Shuttle-*Mir* rendezvous flights and the long-duration stays of seven NASA astronauts on *Mir*. The program also provided for nine Russian cosmonauts to fly on the Space Shuttle. Drawing to a close in June 1998, after four and a half years, Phase I has proven to be an unprecedented learning opportunity for living, working, and conducting research in space. This space research complements an ongoing, robust ground research program. As we move from Phase I into actual ISS assembly and operations, NASA is actively engaged in factoring the Phase I lessons into the broader ISS program.

This monograph is intended to provide an initial overview of the knowledge base acquired, research results obtained, and lessons learned by NASA through Phase I of ISS development. It is also an acknowledgment of the dedication and accomplishments of the *Mir* and Shuttle crews and the efforts of the many engineers, managers, and scientists of both countries who have made this program successful beyond initial expectations. Finally, I would like to recognize the dedication and contributions of our Russian colleagues in having made the Phase I program possible.



Daniel S. Goldin
NASA Administrator



Daniel S. Goldin

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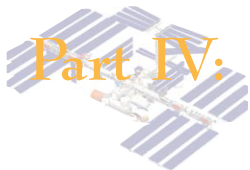


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Part I

A Learning Opportunity

In 1998, the United States and its International Space Station (ISS) partners embark upon a journey of historic proportions. The assembly and operation of the ISS ushers in an era of unprecedented space research capability. The investment by this Nation and its partners in time, talent, and resources has been tremendous, and the fulfillment of the ISS program puts this investment to the test. The United States and its partners seek not only to protect but to maximize this investment, and America's commitment to the Phase I program has done exactly that.

As the Mercury and Gemini programs prepared us for the Apollo missions to the Moon, the Shuttle-*Mir* experience prepares us for the ISS era. Phase I, initiated in November 1993, has been a unique opportunity for the United States and the ISS partners to expand our space experience. In many ways, Phase I has been a rehearsal for the more complex tasks of ISS assembly, logistics, maintenance, and research. Phase I is facilitating the later stages of ISS development through fulfillment of four primary goals:

1. Reduce the risks associated with developing and deploying the ISS;
2. Garner operational experience for NASA on long-duration orbital missions;
3. Conduct peer-reviewed, precursor scientific research in preparation for the ISS; and
4. Learn how to work with our Russian colleagues.

The ISS will involve contributions from at least 15 partner nations, include 4 research laboratories of unprecedented capability, take 45 flights to fully assemble, and operate on orbit for over a decade. We anticipate even more international involvement with the ISS program once full-scale research operations get underway. The Phase I program has given the ISS partners invaluable experience in international space operations. As a test bed for engineering design, scientific research, and international operations, Phase I has allowed us to protect a sizable investment by the ISS partners, while reducing health and safety risks for hundreds of future ISS astronauts. We have improved our understanding of how to use precious resources such as power, water, air, food, crew time, and resupply capability to support a meaningful and dynamic space research program. The time on *Mir* has given the United States and its partners the chance to test hardware and scientific equipment on orbit while exploring new research opportunities for the ISS. As a research effort, Phase I science and engineering investigations have produced data sets that complement broader, ground-based research programs in the physical and biological sciences. The Phase I program has enabled us to explore ways in which to maximize this synergy between flight and ground research in anticipation of the ISS era.

The core module of Russia's seventh, and most current, space station, *Mir* (meaning *peace* in Russian), was launched on February 20, 1986. Following a philosophy of incremental growth, the Soviet Union, and then the Russian Federation, steadily added capabilities and laboratory modules to *Mir*. As part of the Phase I program, the United States helped finance and equip the last two *Mir* modules, *Spektr* and *Priroda*, with scientific instruments. *Spektr* was outfitted to support a variety of life sciences experiments, and *Priroda* with microgravity research facilities. These modules were launched to *Mir* in 1995 and 1996, respectively. The United States also funded the construction and delivery (via the

The Space Shuttle and *Mir* may be of roughly similar mass and size, but they were designed to operate independently in space, not as a part of an orbiting, American-Russian spacecraft complex. Getting these two independent programs to operate in an integrated fashion so quickly required the creative work of scientists, engineers, technicians, and supporting staff from many organizations in the United States and Russia. Less than three years from the initial bilateral agreement, the Space Shuttle *Atlantis* and *Mir* rendezvoused on orbit.

Space Shuttle) of additional solar arrays for the Russian station to supply more power for experiments.

Typically, *Mir* can support up to three people for extended periods and up to six crew members for several weeks at a time. The Russian station has 380 cubic meters of habitable space. Within the modules themselves, different scientific instruments, environmental monitors, and technology demonstration experiments are interchanged regularly in accordance with the cooperative research agendas of the United States, Russia, and our other international partners.

The successful execution of the Phase I program required precise working coordination among a broad array of Russian and American support elements. *Mir* was supplied by three separate space vehicles; it was equipped with both Russian and American research facilities, including hardware provided by other international partners, and supported a crew that traveled to and from the station via either the Space Shuttle or the *Soyuz* spacecraft.

Russian and American technical personnel coordinated between two separate mission control centers, one in Russia and one at the Johnson Space Center in Houston, Texas.

The Space Shuttle first docked with *Mir* in June 1995 (Shuttle flight STS-71). Spektr had just arrived at *Mir* one month earlier, and the Priroda science module was still being outfitted on the ground. For this first docking mission, the Space Shuttle *Atlantis* carried a complete pressurized laboratory known as Spacelab inside its payload bay (pictured here during outfitting operations); the European Space Agency (ESA) built the Spacelab module for advanced Shuttle science operations. When the Shuttle returned to Earth, it carried U.S. astronaut Dr. Norman Thagard home from *Mir*, along with his two fellow *Mir* crew members, Russian cosmonauts Vladimir Dezhurov and Gennadi Strekalov. (The Shuttle delivered cosmonauts Anatoli Solovyev and Nikolai Budarin to *Mir* for the start of their orbital stay.) This marked the first time in history that the Space Shuttle returned to Earth with more crew members than it launched.



Americans and Russians have learned to integrate engineering and technical cultures across international boundaries and aerospace industries. Phase I astronauts trained on three separate spacecraft (Shuttle, *Mir*, and *Soyuz*) through training programs in both the United States and Star City, Russia. While on *Mir*, American crew members functioned as both researchers and flight engineers; this meant that NASA astronauts participated in the maintenance of *Mir*. The coordination of all these activities was a crucial rehearsal for the multinational ISS. The chart below summarizes the major space elements of the Phase I program.

Dr. Andrew Thomas, the seventh and final NASA astronaut to serve on *Mir*, embarked in January 1998 along with scientific equipment for 25 research investigations and technology demonstrations. The last of the Phase I Shuttle flights picked up Dr. Thomas in June 1998, at which time American astronauts had spent more than 975 days on *Mir*, exceeding the time spent in space by our Space Shuttle fleet in its 17 years of operation.

The remainder of this document highlights the lessons learned and research results gar-

MAJOR SPACE ELEMENT	FUNCTION
<i>Soyuz</i> vehicles	Ferry crew and supplies to and from <i>Mir</i> ; emergency crew return vehicle, maximum orbital life of six months
<i>Progress</i> vehicles	Ferry supplies to <i>Mir</i> ; no return capability
<i>Mir</i> Core Module	Station operations, main habitat & living area for cosmonauts
<i>Mir Kvant</i> -Module 1	Astrophysics, biology, Earth observation
<i>Mir Kvant</i> -Module 2	Space walk access, materials exposure to space
<i>Mir Kristall</i> Module	Biological and materials processing technology development
<i>Mir Spektr</i> Module	Life sciences and technology research, remote sensing of Earth's upper atmosphere*
<i>Mir Priroda</i> Module	Microgravity research, technology validation, Earth remote sensing
<i>Mir</i> Docking Module	Serves as the port for Shuttle- <i>Mir</i> dockings
Space Shuttles	Research laboratory, crew transport, logistics and <i>Mir</i> resupply, maximum orbital stay of 18 days in current configuration
Spacelab (developed by ESA)	Research laboratory for life and microgravity sciences and applications—carried in the Shuttle payload bay
Spacehab (commercially developed)	Experiment housing, logistics and supplies transport—carried in the Shuttle payload bay



Russian elements



Joint U.S.-Russian developed elements



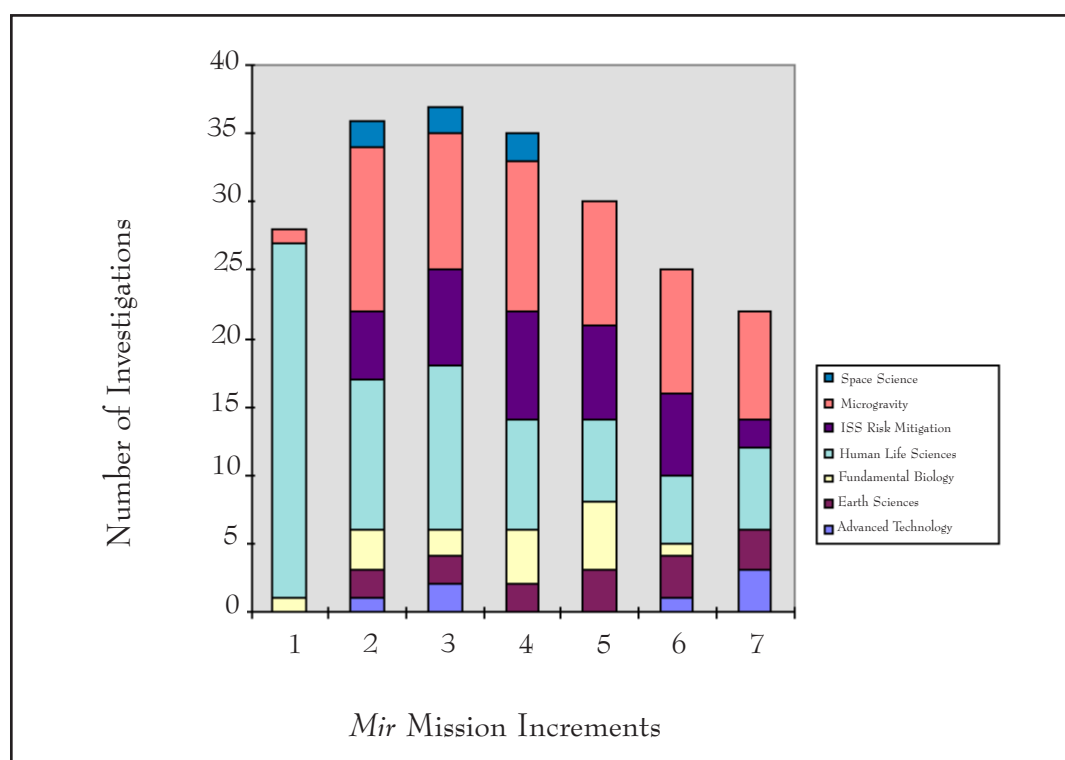
U.S. elements

* Not available following the June 1997 collision with the *Progress* vehicle

NASA undertook Phase I research efforts in addition to its ongoing research agenda aboard the Space Shuttle. Planned Shuttle research proceeded in parallel with the added experimental efforts and operational responsibilities of the Phase I program.

The United States tracked the Phase I program in seven increments. During each increment, a NASA astronaut resided on Mir. The graph represents the number of science and engineering investigations carried out on Mir during each Phase I increment.

nered to date from the Phase I program. Overall, the structure of the narrative reflects NASA's four goals (see page 5) for the Phase I program. Research results are provided in a separate section (Part III) in order to treat more fully the investigations and their accompanying benefits for Earth and space. Part II, "Lessons for the International Space Station," discusses Reducing Risks Through Engineering Research, Operating a Space Station, and Working With Our Russian Colleagues. Part III, "The Conduct of Research," details advances in Linking Ground and Space Research, Understanding the Orbital Laboratory, Looking After Our Health, and Using the Space Environment. Part IV, "An Investment in Our Future," concludes the main body of this report by highlighting the critical relevance of the Phase I program to the successful continuation of the ISS endeavor.



Shuttle Mission Commander Robert (Hoot) Gibson (foreground) greets Russian Station Commander Vladimir Dezhurov as the Space Shuttle and Mir docked together for the first time on June 29, 1995. The occasion brought memories of the historic 1975 Apollo-Soyuz "handshake in space." The crews of the Shuttle and Mir followed this exchange with a series of gifts and formal greetings before transferring supplies and initiating joint research operations.



Part II Lessons for the International Space Station

The Phase I partnership offered the United States and Russia a singular opportunity to work with and to learn from each other. The Phase I program provided the United States with more than 2 “astronaut-years” of space station operational experience. For the ISS partnership, this experience will enhance our abilities to assemble, operate, and conduct research on an international, long-duration space platform.

Reducing Risks Through Engineering Research

Space is a uniquely challenging environment. Accommodations must be made for solar and cosmic radiation, the presence of meteoroids, space debris, vacuum, temperature extremes, and the absence of gravity’s effects. The exact modifications we make to our Earth-based technology and techniques in overcoming these challenges depend upon the length of time we plan to actually spend in space. Phase I was an opportunity to study and validate space station engineering considerations that differ from those encountered with the Space Shuttle. Through hands-on engineering research in a space station environment, we have been able to reduce the risks we will face during ISS assembly and long-duration operations. In particular, we had the opportunity to conduct a number of hardware and procedural demonstrations.

For example, preliminary results indicate that NASA’s model for the trapped radiation environment around Earth underestimates the radiation exposure risk to astronauts during periods of high solar activity and overestimates the levels during periods of low solar activity. NASA has used the Phase I measurements, together with Shuttle data, to develop corrections to the existing radiation model, improving the average accuracy of radiation health risk predictions. NASA is working to develop improved planning and scheduling practices to minimize astronaut radiation exposure during extravehicular activities (EVA’s), also known as “space walks.”

Space walks will be important during the assembly and operations of the ISS. The ISS module connections, solar array emplacement, and support truss deployment will require the active participation of astronauts. During research operations, some externally mounted experiments will need to be put in place and retrieved by astronauts on EVA’s. Under the Phase I program, two science modules were modified and added to *Mir* (*Spektr* and *Priroda*). NASA was actively involved in funding and equipping research facilities for these modules. The arrival of the redesigned modules necessitated the rearrangement of existing modules and systems on *Mir*, requiring a number of EVA’s. Crews installed two new solar arrays on *Mir* under the Phase I program and retrieved a portion of one of the

Monitors on the outside of the Russian station found that *Mir*’s surface was being contaminated by residue from its own attitude control propellant. In an effort to avoid the same pitfall, ISS propellant venting procedures have been changed.

Astronaut Scott Parazynski prepares for a space walk. EVA's will be very important in the assembly of the ISS. In preparation for the ISS, Phase I astronauts and cosmonauts methodically tested techniques and tools for specific ISS assembly and maintenance tasks.



original solar arrays, transporting it via the Shuttle for ground analysis. Analyses indicate that the solar arrays suffered significantly more damage than anticipated from *Mir* waste elimination and Shuttle thruster residue. These findings have resulted in modifications to waste elimination procedures and protocols for ISS-Shuttle “proximity operations.” NASA is factoring these results into the maintenance and replacement schedules for the ISS solar arrays.

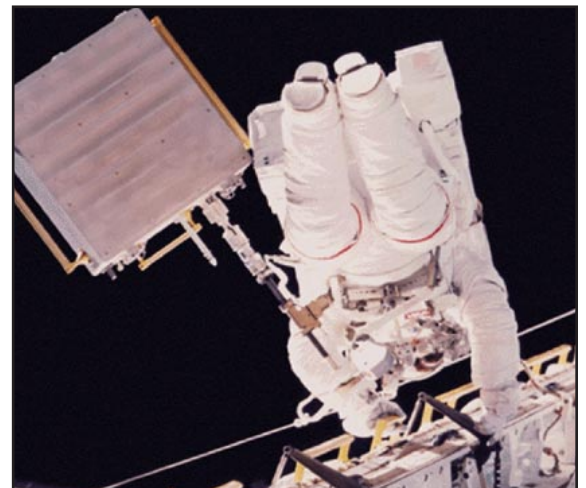
U.S. astronauts have participated in several EVA's conducted solely from *Mir* (as opposed to those conducted from the Shuttle during docked operations). Dr. Jerry Linenger was the first to use the Russian Orlan EVA suit; his task was to deploy U.S.

Phase I space walk experience highlighted the need for external station viewing capability. NASA is working to develop robotic fly-by cameras to assist in ISS EVA operations and station inspections.

science equipment and to gain experience with Russian EVA hardware and procedures. Dr. Michael Foale participated in an important space walk to assess the damage to *Spektr* caused by the June 1997 collision between the station and a Russian *Progress* vehicle. Dr. David Wolf took part in a *Mir* space walk to further our experience with the Russian EVA suit and to conduct U.S. research. As a precursor to Dr. Foale's EVA, joint criteria and guidelines necessary to certify the safety of an unplanned EVA were developed. The knowledge we take away from these experiences is preparing us for the multinational endeavor of onorbit ISS assembly.

Large space structures such as *Mir* and the ISS are considered “flexible” because they are composed of multiple modules and may oscillate when forces are applied at certain points. Large suspension bridges are good examples of flexible structures. Engineers must carefully calculate a bridge's design in order to avoid a final structure that could accidentally shake itself apart. Because it is impossible to build a full-scale model of the ISS on Earth (it would not be able to support itself in gravity), the structural behavior of the ISS can be predicted only through the use of precise mathematical and engineering calcula-

In March 1996, while the Space Shuttle *Atlantis* remained docked to *Mir*, U.S. astronauts Richard Clifford and Dr. Linda Godwin placed the *Mir* Environmental Effects Payload (MEEP) on the outside of *Mir*'s docking module. Analysis of the MEEP will help researchers understand what types of particles or contaminants the ISS might contact in its 51.6-degree orbit. Here, Dr. Godwin is seen carrying a component of the MEEP along the Shuttle payload bay. The MEEP stayed on the outside of *Mir* for 18 months and was returned to Earth for analysis in October 1997.



tions. This approach was used to “model” the behavior of the combined Shuttle-*Mir* docked complex when the Space Shuttle used its own thrusters to affect *Mir*’s orientation. The equations accurately predicted the complex structure’s behavior. The use of a “validated” model for predicting the response of the ISS to certain forces permits ISS design and construction to proceed with a higher degree of confidence. These tests also validated the ability of the Space Shuttle to deploy and maneuver elements of the ISS during assembly.

NASA has garnered practical experience on *Mir* in resolving a variety of space station problems. For example, *Mir* crews successfully dealt with the station’s loss of electrical power, a fire resulting in temporary atmospheric contamination, and a cabin pressure leak. In all instances, Russia, with U.S. support, resolved these problems to permit the continuation of mission activities.

Problems on *Mir* have led to a number of hardware, software, and procedural changes for the ISS. A February 1997 fire aboard *Mir* caused NASA to re-evaluate ISS fire control options. *Mir* operations demonstrated that a temporary shutdown of the station ventilation system can help prevent a fire from spreading. ISS software was subsequently modified to allow a temporary, single-command ventilation shutoff between modules. In addition, the incident made mission planners more cognizant of the location of critical hardware such as medical kits and fire extinguishers; ISS crew members must be able to reach emergency equipment quickly. The depressurization of the *Spektr* module after a collision with a Russian *Progress* vehicle in June 1997 validated the U.S. design (no cables running through open hatches) and demonstrated the importance of maintaining clear station passageways. *Mir* crew members had to rush to disconnect cables that connected the leaking *Spektr* module to the rest of the station before they could close the hatch. *Spektr*’s depressurization also led to the redesign of some critical Russian ISS components; the intent is to make them more robust in the event of isolated depressurization on the ISS. The experience has also pointed out the need for astronauts to have portable life-support sensors to monitor total pressure, oxygen content, and similar parameters. Researchers have also found that some corrosion on the inside of *Mir* resulted from otherwise benign contact

*The **Mir** experience confirmed the need for redundant access and egress points on a space station. Early in the assembly sequence, the ISS will have two separate airlocks.*



Pictured here during ground outfitting operations, the Functional Cargo Block, or FGB, will be the first ISS element placed into orbit. A U.S.-funded, Russian-built component, the FGB is scheduled for launch on a Russian Proton rocket in 1998. Two weeks later, the U.S. Space Shuttle will capture the FGB and attach it to the U.S. node in the first onorbit assembly stage of the ISS.



Astronaut Thomas Akers transfers liquid nitrogen Dewars containing frozen samples of proteins to be grown into 3-D crystals on Mir. Each time the Shuttle docked with Mir, it carried a significant quantity of logistics material and experimental equipment to and from the Russian station. The exchange of materials and resources between the Space Shuttle and Mir has led NASA to modify ISS supply procedures to increase efficiency.

between two dissimilar metals. When humidity levels on *Mir* are high, different metals can react corrosively at their points of contact. Protective coatings have been added to some ISS cooling lines to prevent similar problems on the international station.

Evaluations of the space station environment and hazards have led planners to alter the size and location of the ISS emergency crew return vehicle (CRV). Instead of having two smaller CRV's attached to the station, as originally intended, NASA and ESA are collaborating to build a craft capable of returning all seven ISS crew members to Earth in a single vehicle. To ensure that all crew members have access to a vehicle in the event of an emergency, one large CRV and one *Soyuz* vehicle will remain attached to opposite sides of the station at all times. NASA is currently assessing the need for a second large CRV.

Operating a Space Station

NASA fully expected that operating a space station would differ from operating a craft such as the Space Shuttle. These differences stem from the fact that Shuttle missions are short, well-defined missions of about 10 days, while station has ongoing operations that will see changes to the planned activities due to onboard circumstances. Our experiences aboard *Mir* have exceeded our expectations and allowed us to review and revise our ISS operations plan. The Phase I program has given us insights into long-term space operations that will help the ISS substantially reduce uncertainties while increasing station efficiency and operational safety.

Events on space stations often require last-minute changes to the manifest (inventory) of resupply flights. Frequent causes for these changes include hardware failures of vehicle systems or experiments. NASA underestimated this element for Phase I, but the Shuttle program has exhibited outstanding flexibility in responding to changing requirements on *Mir* and has paved the way to better support for the ISS.

Phase I lessons have emphasized that astronaut training objectives for long-duration crew members will differ from those NASA has traditionally employed for Shuttle crews. It is essential to address psychological factors early to maintain crew morale and efficiency throughout long-duration stays. Overall, mission training must be more general-skills-oriented than the intensive procedural practices that are emphasized in Shuttle training. Skills training will provide better flexibility and is more cost-effective for onorbit station operations.

In conjunction with this emphasis on skills training, NASA will schedule onorbit crew activities for the ISS very differently than the way it does for Space Shuttle missions. Shuttle missions are planned in great detail before flight to make optimum use of every available moment. Station crews will perform a wide range of duties, both

Initial plans for the ISS called for the use of duplicate backup systems in the event of failures. However, working with our Russian colleagues has taught us that it is sometimes both practical and economical to use backups that work in an entirely different manner than their primary system. For example, the Russian station has three entirely different ways to generate oxygen, a capability that the ISS will now match.

planned and unplanned, and the Phase I experience has taught us that it is neither practical nor feasible to create extremely detailed day-to-day timelines for long-duration space station operations. The Russian program uses a more flexible approach to scheduling, in which crew members apply the fundamental skills they learned in training to the tasks required by the actual priorities of the day. For instance, solving a problem with an experiment's equipment may require sending a replacement part or repair tool to the station on an interim flight. Meanwhile, rearranging the research agenda would free time later to complete the problematic experiment once the repairs are complete. This approach ensures that long-term goals for the entire mission are met. Phase I has verified ISS program planning and timelining tools; modifications and enhancements are being made to ISS flight planning strategies and concepts on the basis of this experience.

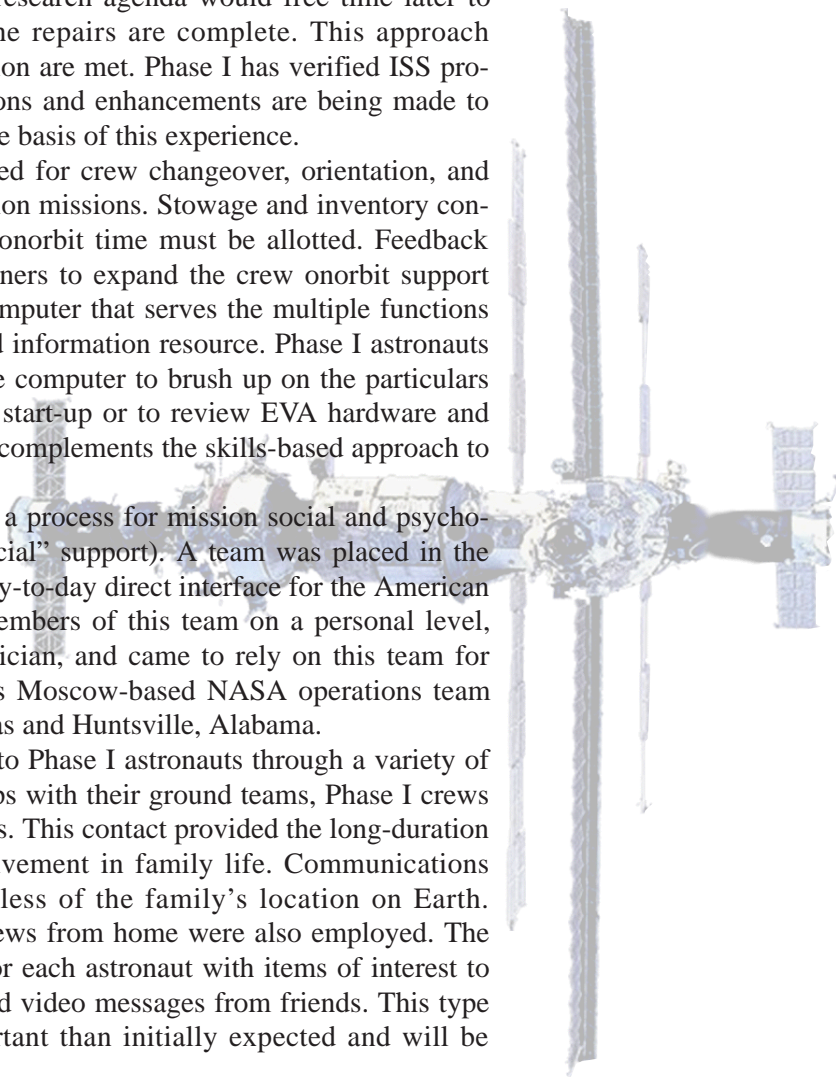
We found that more time should be planned for crew changeover, orientation, and experiment setup at the beginning of long-duration missions. Stowage and inventory control are also crucial areas for which adequate onorbit time must be allotted. Feedback from early Phase I astronauts led mission planners to expand the crew onorbit support system, which consists primarily of a laptop computer that serves the multiple functions of training, entertainment, language teacher, and information resource. Phase I astronauts since Dr. Shannon Lucid have used the portable computer to brush up on the particulars of experiments immediately before experiment start-up or to review EVA hardware and procedures before a space walk. This capability complements the skills-based approach to training discussed earlier.

Phase I work has led to the development of a process for mission social and psychological support (often referred to as "psychosocial" support). A team was placed in the Moscow Mission Control Center to provide a day-to-day direct interface for the American astronauts on *Mir*. The astronauts knew the members of this team on a personal level, especially the mission manager and crew physician, and came to rely on this team for general support and answers to questions. This Moscow-based NASA operations team was in turn supported by teams in Houston, Texas and Huntsville, Alabama.

Critical psychosocial support was provided to Phase I astronauts through a variety of means. In addition to close personal relationships with their ground teams, Phase I crews required frequent contact with family and friends. This contact provided the long-duration crew member with a sense of continued involvement in family life. Communications included teleconferences with family, regardless of the family's location on Earth. Electronic mail and other methods of getting news from home were also employed. The crew onorbit support system was tailor-made for each astronaut with items of interest to him or her, including a family picture album and video messages from friends. This type of activity turned out to be much more important than initially expected and will be emphasized for the ISS.

Maintenance and repair operations are primary drivers of training and scheduling requirements on space stations. Unlike the Space Shuttle, on which most maintenance is performed after it returns to Earth, ISS crews will be required to make almost all repairs on orbit. Maintenance will be anticipated and accommodated in station scheduling. Phase I has given us valuable, first-hand experience in balancing station maintenance and research operations.

The *Mir* experience has shown that noncritical station systems can be operated until they fail, and only then exchanged or overhauled as part of routine maintenance and





The Russians use their Soyuz vehicles to ferry crews to and from Mir. The last Soyuz to arrive at the station while Mir is occupied is always left attached to act as an emergency return vehicle. As Mir crews return to Earth, they do so in this Soyuz vehicle, which is replaced by the ascending crew's spacecraft. The Russians have used the Soyuz craft to make fly-around inspections of the station; the vehicle's thrusters can also be used to orient the station as a back-up to Mir's attitude control capability.

repairs. This approach will be implemented on the ISS since it reduces the overall demand for spare parts and minimizes costs. Regarding back-ups for critical equipment, the Phase I experience has shown that the crew and station can recover from many potentially hazardous situations through the use of robust backup systems, which sometimes use totally different technology than the primary system that failed. It is also clear from Phase I experience that spare parts for critical systems must be available on board for immediate use. We have learned in our work with the Russians that all station activities must be planned such that there is always a path to the crew return vehicle, and that the vehicle should always be ready if needed to return the crew safely to Earth.

Phase I gave the American and Russian space programs the opportunity to become familiar with each other's experiences and infrastructure. As a result, we can better combine our capabilities to maximize mission resources. The same type of teamwork will enable the partner nations to make the most of their space elements to supply the ISS safely and efficiently. One example of this teamwork was the use of by-product water from the Space Shuttles' electrical power generation. The Shuttle fuel cells combine oxygen and hydrogen to form water and power. Instead of following the standard practice of dumping this water overboard, the Shuttles used this by-product to supply *Mir* with potable water. On *Mir*, the water was either used for human consumption or converted back to oxygen and hydrogen by using solar power. The Shuttle also used its systems, on occasion, to revitalize *Mir's* atmosphere during docked

operations. By utilizing existing resources, space was freed on supply missions to *Mir* for other items, such as scientific equipment.

Making the best use of all ISS partners' spacecraft will ensure that the ISS is supplied as efficiently and safely as possible. During Phase I, NASA had the opportunity to become familiar with the capabilities and reliability of the Russian *Soyuz* vehicle and *Progress* supply craft. The cargo carrying capacity of the Space Shuttle was used to significantly advance the state of *Mir* research, allowing researchers to return both scientific samples and engineering prototypes to Earth for analysis. NASA's role in sample and equipment return was excellent practice for Shuttle operations that will be used to build and supply the ISS. Each type of vehicle has strengths and weaknesses, and Phase I has provided the opportunity to optimize operational plans.*

It is important for ISS crew members to be familiar with all ISS equipment provided by every partner nation. The United States and Russia used Phase I to get a head start on achieving this operational flexibility. For instance, NASA astronauts were trained to use the *Soyuz* return vehicle if the need arose. Similarly, cosmonauts and astronauts could use either American or Russian launch and entry space suits (suits that provide an individual

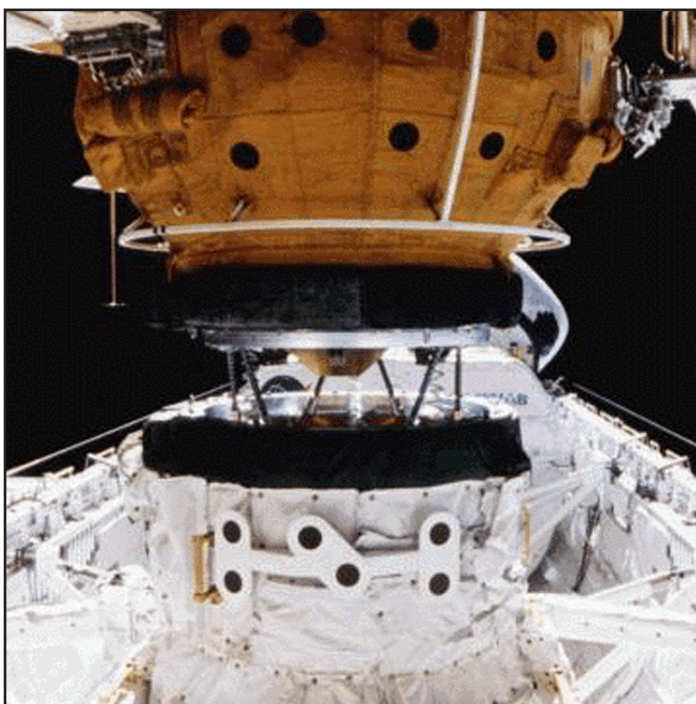
*Eventually, the ISS may be serviced by as many as six different space vehicles: The American Space Shuttle, the Russian *Soyuz* and *Progress*, the European *Ariane* Automated Transfer Vehicle (ATV), the Japanese H2, and the American/European CRV. *Progress*, ATV, and H2 do not carry crew.

life support system and are worn inside the spacecraft) and other support equipment while traveling between the ISS and Earth. Over the course of Phase I, crew members designated to participate in EVA's were also trained to use both types of EVA space suits. Additionally, both the Shuttle and *Mir* airlocks were used for space walk access. This ability to work in concert with different national facilities and equipment will enable future ISS crews to achieve higher standards of efficiency and safety.

Space stations are composed of very fragile and sensitive components such as optics and solar arrays; space vehicles working near or docking with stations must maneuver very carefully with minimum thruster firing. For example, firing a thruster too close to a solar panel could damage the energy-gathering solar cells or cause the array to oscillate, potentially bending or breaking it. Significant damage to an ISS solar array could decrease the transmission of power to the station, affecting its ability to support research, or even affecting its safety. Excessive speed during docking could also damage the docking module or adversely affect station orientation. A series of successful rendezvous operations with *Mir* allowed NASA to fine-tune its approach and docking protocols for the ISS.

NASA has chosen to adapt a Russian docking mechanism for the ISS, saving time and development costs for the ISS program. Phase I operations have flight-proven this type of docking mechanism, along with a number of sensors that will enhance rendezvous capability with the ISS. We also learned that a series of externally mounted tracking lights on the station could greatly increase visibility during docking operations. Plans for the ISS have been modified to add this feature.

NASA also used the Phase I experience to modify activities that occur after flight. NASA did not fully appreciate the attention that should be given these activities. For example, we have been able to modify the astronauts' rehabilitation programs upon their return to the gravity environment (see Part III).



NASA funded and delivered a docking module to Mir as a part of the Phase I program. This module, seen here above the payload bay, ensured adequate clearance between the Space Shuttle and the Russian station during rendezvous. The module was delivered by the Space Shuttle in November 1995 and became a permanent part of Mir.

All U.S. crew members stationed on *Mir* had extensive training in *Mir* systems and operations protocols. Since the flight of Dr. Shannon Lucid, they all qualified for the designation “Cosmonaut Flight Engineer 2” from the Russian Space Agency. Our experiences in “cross-training” crew members from different backgrounds is a forerunner for training the multinational crews of the ISS.

Working With Our Russian Colleagues

With the exception of the Apollo-Soyuz Test Project in 1975, U.S.-Soviet space cooperation was largely limited to the exchange of scientific data. Two decades ago, the American and Soviet space programs took the first step in working together in human space flight. Today, the Phase I program has given the United States and its partners the opportunity to integrate and validate engineering, management, and operational approaches before the much more complex tasks of assembling, operating, and conducting research on the ISS.

Coordinating and integrating two robust space programs and their supporting infrastructures that have operated independently for decades has been a formidable task. Phase I experience strengthened the professional ties between American and Russian engineers, scientists, technicians, and managers. By working closely throughout the Phase I program, we advanced the working relationships and intercultural understandings that will allow ISS assembly, operations, and research to proceed smoothly.

All the planning, training, and logistics for Phase I was coordinated with Russian specialists and instructors well before the first Phase I mission. American training teams lived and worked in Star City, Russia to help coordinate and conduct the U.S. science training for both the astronauts and the cosmonauts. NASA concluded Phase I with a very thorough understanding of how the Russians plan and train for a flight after 4 years of work-

“The first time is always the hardest.” The first U.S. astronaut flight on Mir was especially complex. Dr. Norman Thagard traveled to Mir in a Russian Soyuz capsule in March 1995 and returned via the Space Shuttle four months later. Here, Dr. Thagard is seen in his sleep station aboard Mir’s Core Module. Medical procedures, communications standards, and operational practices were all new for this mission.



ing shoulder to shoulder with our Russian colleagues.

Creating integrated control center operations for Phase I was challenging. We had to learn to interpret each other's "standard documentation" and decide how to allocate and track responsibilities between the two different space organizations. We overcame time differences and language barriers and successfully integrated our national systems for global communications coverage with the station. Crew members communicated with ground personnel in both the United States and Russia. This coordination added a margin of safety for the execution of sensitive station operations, during which unbroken communications with ground personnel were essential. Many Americans who will operate and use the ISS participated in this integration and will take this knowledge with them through the next phases.

Phase I research operations provided the international scientific community with a critical rehearsal for the ISS. The Phase I research program involved investigators from universities and research institutes across the Nation and throughout the world. Phase I investigators included leading scientists from Canada, France, Hungary, Japan, Russia, the United Kingdom, and the United States. Throughout Phase I, American, Russian, and other international investigators used each others' laboratory equipment, shared data and specimens, and will continue to plan new and exciting projects. ISS research will be performed by scientists from all over the world, whose experiments will have been peer-reviewed and selected by international committees of experts to ensure that the very best scientific work is done on the ISS.

The ISS will include laboratory modules supplied by the European Space Agency, Japan, Russia, and the United States. Canada will provide a Remote Manipulator System (a "robotic arm" similar to the one used on the Space Shuttle); Brazil, France, Germany, Italy, Spain, and Ukraine will also provide hardware for the ISS. By working together in



The ISS assembly schedule will depend on a series of Shuttle flights launching on time. The Phase I program has given NASA the opportunity to carefully evaluate and modify Shuttle launch operations to minimize the possibility of a launch "slip" while maintaining the highest standards of safety. The approximate window of opportunity for launching to Mir and the ISS orbit is just 9 minutes each day.

the first phase of ISS development, the United States, Russia, and other ISS partners have actively prepared for multinational ISS operations.

Phase I multinational experience was enhanced by the presence of European and Canadian astronauts on a number of Phase I flights. Canadian, French, and ESA astronauts have flown on the Shuttle during *Mir* rendezvous flights. On three of these occasions, Russian cosmonauts were also on board. U.S. astronaut Dr. Jerry Linenger shared *Mir* with his Russian colleagues and a cosmonaut from the German Space Agency. Likewise, both Dr. Shannon Lucid and Dr. David Wolf shared *Mir* with French cosmonauts during their orbital stays. These experiences taught us how to operate with a multinational crew in anticipation of the ISS.

The ISS partnership was cemented on January 29, 1998 when the governments that constitute the core of the partnership came together to sign the ISS Intergovernmental Agreements. In conjunction with this signing, the space agencies of the partner nations signed Memoranda of Understanding. Participating in the ceremony and seated are, from left to right, Yuri Koptev of the Russian Space Agency, Antonio Rodota of the European Space Agency, Daniel S. Goldin of the U.S. National Aeronautics and Space Administration, William Evans of the Canadian Space Agency, and Isao Uchida of the National Space Development Agency of Japan.



The Conduct of Research

Since the Skylab program concluded in 1974, U.S. human-tended microgravity research has been limited to durations of up to 18 days, the current maximum length of a Space Shuttle mission. The Phase I science program provided the international scientific community access to a research environment with many characteristics similar to the ones that will be found on the ISS. Researchers used the *Mir* opportunity to familiarize themselves with operational protocols and techniques, to test equipment, and to conduct experiments as precursors to ISS research. Many of the researchers have flown experiments on the Shuttle and on Spacelab missions. Often their goal was to conduct experiments on *Mir*, similar to their previous Shuttle work, to identify the differences in results between short-duration and long-duration space flight, and to complement their ongoing ground-based work. In addition, Phase I gave scientists a “hands-on” preview of day-to-day scientific operations in a long-duration, orbiting research facility.

About 150 peer-reviewed investigations, spanning a wide variety of research disciplines and experimental programs, were conducted aboard *Mir* as part of the Phase I research program. A NASA strategic planning group coordinated both the Space Shuttle and *Mir* research elements for the Phase I program. This section examines how the knowledge gained from Phase I has expanded the links between ground and space research, strengthened our understanding of the orbital laboratory, added to our knowledge about human health in space, and improved our ability to fully utilize the resources of a long-duration space research facility.

Linking Ground and Space Research

NASA maintains a vigorous, peer-reviewed program of ground-based research as the backbone for its space research efforts. Before any research experiment is considered for space flight, investigators must have demonstrated the need for a microgravity environment. Once a need has been determined, additional work must be done to equalize the effects of variables common to space and ground research, such as temperature or day-night rhythms. The effective use of the microgravity environment requires the use of simulations, modeling, or drop towers to refine ground-based models, thus ensuring the qual-

NASA aggressively sought out and followed the guidance of external reviewers in order to ensure that competitive scientific research was conducted on *Mir*. The *Mir* Science Working Group, the NASA-NIH Advisory Subcommittee on Biomedical and Behavioral Research, NASA's Life and Microgravity Sciences and Applications Advisory Committee, and the NASA Advisory Council all provided guidance and oversight for NASA's Phase I research program. This constant flow of input from external advisory bodies will continue during the ISS era. (See Appendix C for a complete list of the review committees associated with the Phase I program.)

Experiments on *Mir* successfully verified a wireless computer network that can be used on the ISS to enhance communications among investigators on the ground, crew members, and station research payloads. Wireless communications will eliminate the typical restrictions on movement associated with cable connections.

ity and relevance of space research. Flight experiments thus complement ground-based programs by allowing investigators the opportunity to manipulate the effects of gravity after suitably accounting for other environmental variables.

The synergy between ground and space investigations was evident in Phase I cell culture research. A complex experiment, involving bioreactor technology resulted in the first successful tissue engineering experiment with cartilage cells. Although additional experiments are needed to explore the mechanisms underlying tissue formation in space, these experiments form the basis for controlled experiments with

human tissues that could clarify the requirements for successful tissue engineering on the ground.

In the microgravity sciences, NASA research performed on board *Mir* in fluid physics, materials science, and combustion science directly complemented the body of knowledge derived from Earth-based research in these fields. Phase I combustion studies, for example, focused on aspects of the burning process, fuel efficiency, fire spread and prevention, and fire-extinguishing mechanisms in microgravity. Comparing microgravity results with those from ground-based studies increased both the sophistication of computer models and the application of the knowledge derived from ground-based research. Similarly, Phase I Shuttle experiments concerned with the study of granular materials could significantly advance ground-based efforts in earthquake engineering, building standards, slope stability, soil erosion, and the transport and handling of granular materials.

More detailed information on the results of Phase I research can be found in the sections that follow.

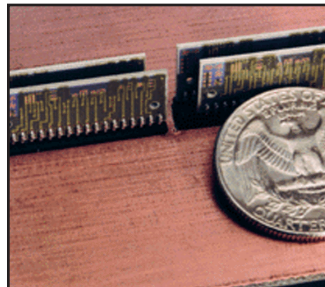
Understanding the Orbital Laboratory

The harsh environment of space requires that the space station protect its crew members from radiation, temperature extremes, vacuum, and debris. The station must also provide satisfactory working conditions for conducting delicate scientific experiments—many of which are much more sensitive to changes in pressure, vibration, or atmospheric composition than are human crew members. Finally, the status of environmental conditions—essentially inside “weather reports”—must be made available in a timely manner to scientists whose experiments are underway.

The Van Allen radiation belts, a zone of high radiation trapped far above the Earth, tend to “dip down” over the South Atlantic Ocean. Spacecraft flying through this region—and especially individuals participating in an EVA—risk exposure to excessive radiation. Research from the Phase I program indicated that this “dip,” known as the South Atlantic Anomaly, has moved 6° west and 2° north since it was last measured during the Skylab program. The Phase I data allow us to make provisions on the ISS to minimize unnecessary radiation exposure for astronauts, radiation-sensitive equipment, and scientific experiments.

Because of the nature of its mission, a space station’s life-

NASA has been working to develop “real-time,” miniature environmental monitors for the ISS, known as “electronic noses.” The noses can detect changes in air quality on the spot. This may minimize the need for air-sample storage and postflight analysis. Work on Mir has helped NASA clarify the manner in which these sensors might be used to complement the broader ISS environmental monitoring system. A component is shown with a quarter for size comparison.



support system depends more on recycled fluids and gases than does a spacecraft such as the Space Shuttle. NASA scientists began monitoring *Mir*'s air, water, and internal-surface cleanliness months before the arrival of the first U.S. crew member. This preliminary work allowed us to determine the sensitivity of *Mir*'s environment to various contaminants, such as bacteria and molds. The *Mir* results will serve as a valuable reference to assess the performance of long-term life-support systems on future space stations. NASA is working with the Russian Space Agency to establish joint environmental standards for the ISS.

The *Mir* experience has shown the need for a number of contingency plans in case of atmospheric contamination of the ISS. The ISS will have crew gas masks that can be plugged directly into the station's oxygen supply. The station will also provide breathing masks to filter airborne particulates and over-the-head charcoal masks to filter out traces of dangerous gases.

The presence of naturally occurring microbes in the human environment can affect both crew health and the quality of station research results. NASA and its partners plan to closely monitor the microbial environment on the ISS. An analysis of the microbes on *Mir* has shown that their types and levels are comparable to those found on the Space Shuttle. Information on the long-term microbial environment on *Mir* will provide a baseline for acceptable levels of microbes on board the ISS.

Many *Mir* and ISS experiments are sensitive to changes in the microgravity environment. Crew movements and *Mir* (or ISS) "stationkeeping" activities (movements of the space station to maintain altitude and attitude) create small accelerations (vibrations) of the research platform, which could either disrupt experiments or result in anomalous readings. Over the course of Phase I, we collected over 3 years' worth of data on the *Mir* acceleration environment. This information will help us plan the best time to run vibration-sensitive experiments on the ISS. For instance, extremely sensitive investigations may need to be scheduled during the crew sleep cycle or simply whenever no exercise is scheduled. In addition, we are testing vibration-damping systems designed to isolate both entire laboratory modules and individual experiment racks from disturbances in the microgravity environment. Although *Mir* and the ISS will respond differently to forces or vibrations, our Phase I work on vibration-isolation techniques has prepared us for efficient assessment and management of similar disturbances on the ISS.

Looking After Our Health

Microgravity presents both challenges and opportunities for human health. On the one hand, space flight causes a number of changes within the human body that can present problems for astronauts, especially when they return to Earth. NASA's biomedical research on *Mir* was aimed at learning how the effects of long-duration space flight differ from those of shorter stays in space and how we can best protect crew members on the ISS. NASA and Russian physicians worked together to ensure that the Phase I crews received the best physical and psychological care possible



Exercise is an important aspect of maintaining crew health. In this photograph, Dr. Michael Foale exercises on the Mir treadmill. The Phase I program successfully demonstrated a treadmill vibration-isolation system. The system isolated the surrounding environment from the disturbances of the exercising crew member. This proven concept will now be used on the ISS.

during their training and flight periods on *Mir*. This system of joint care and oversight helped us prepare, in a variety of ways, for when multinational crews will work together on the ISS. Although the space flight environment may challenge us to protect the human body, we also know that microgravity can be a powerful tool in the field of biotechnology. Phase I research has helped advance this field in anticipation of its importance on board the ISS.

The Russian program has included more than two decades of experience in the medical and psychological care of long-duration space crew members. Although some U.S. medical practices differ from the Russian approach, American and Russian medical experts developed a system of in-flight health care on *Mir* that combined the best of Russian and American space medicine. With this “best medical practices” system, improvements were made by using observational evidence of the best methods of patient care, according to patient satisfaction and outcome. Regardless of the country of origin, the best methods of patient care will continue to be set as benchmarks for medical care in space. These practices are subject to continuous revision as we add to our base of knowledge from the Phase I program.

Before their flights, U.S. astronauts in the Phase I program trained at the Gagarin Cosmonaut Training Center in Star City, Russia. During this time, those astronauts and their dependents received limited medical care from the onsite NASA medical clinic, as well as expert medical consultation via a telemedicine system linked to NASA medical facilities in the United States. Such a system enhanced “real-time” medical care decision making during astronaut training. During Phases II and III of the ISS program, this linkup will continue to support American and international astronauts while they prepare to assume their duties as ISS crew members.

Since unforeseen medical events do occur on *Mir*—and will on the ISS—NASA has worked with an international group of physicians to enhance in-flight medical capabilities and to stay abreast of the continuing expansion of medical knowledge. Events on *Mir* reinforced the philosophy of providing the best clinical care to address medical events on the ISS. Already planned for use on the ISS, a cardiac defibrillator was delivered to *Mir*, expanding the Russian station’s ability to provide medical care if required. Plans for ISS medical care continue to evolve as we analyze the Phase I experience.

Our *Mir* experience has shown us the importance of balancing in-flight medical capabilities with expertise from the ground. NASA has pioneered the use of the Internet as a platform for advanced telemedicine systems. The Phase I program was an important test bed for this project. Astronauts and cosmonauts were in contact with medical doctors on the ground through a visual and audio communication system. Private medical conferences and real-time medical monitoring of the astronauts from the ground were routine. NASA assigned a ground-based physician to each long-duration mission; this doctor was the primary medical

In the event of injury to a crew member, NASA has developed a medical restraint system to hold a crew member and medical hardware in place while medical care is provided in microgravity. During the Phase I program, NASA tested this restraint system on *Mir* and validated its effectiveness for the ISS.

contact throughout an astronaut's stay on *Mir*. Such onsite availability helped the United States and Russia coordinate medical responses to environmental contamination situations on *Mir*, such as a leak of the coolant ethylene glycol into *Mir*'s atmosphere. Through the use of telemedicine capabilities, ground-based medical personnel assessed the effects of the contamination on astronaut physiology and determined the appropriate level of corrective action. Telemedicine offered crew members on *Mir*, and eventually on the ISS, an assurance that medical expertise is always available.

In response to concern for crews being overwhelmed with wires and monitoring equipment while on orbit, NASA developed the "heads-up" display, which is a small, wireless headset that communicates audio and visual data to the astronaut. This allows crew members to call up the information they need without moving to a display panel. With this headset, a crew member can receive imagery (such as diagrams), text (such as task lists), or biofeedback data from miniaturized, wireless biosensors. Studies on crew movements and body positions in microgravity can also be undertaken using a "smart suit" that NASA is currently developing. Information from Phase I studies on movement and posture in microgravity may be incorporated into the suit's design. The "smart suit" incorporates a suite of wireless sensors that transmit information on the wearer's leg movements, arm positions, and even posture. The suit can be worn while the astronaut goes through the daily routine, accumulating data without hindering freedom of movement.

Monitoring the health of the astronauts helps us understand how the human body reacts to living in space. One of the major consequences of space flight is cardiovascular deconditioning. Astronauts lose up to 20 percent of their total blood volume during their first few days in space. On return to Earth, the lesser blood volume often causes light-headedness and even fainting. Phase I research has helped scientists to determine the causes of this fluid loss in space flight by giving researchers a set of long-duration data to compare with Space Shuttle short-term data on cardiovascular deconditioning. Phase I research also revealed an apparent increase in cardiac dysrhythmia after about 70 days of space flight. Indications so far are that this is a benign response to space, but the phenomenon is still being studied.

When in space, astronauts also experience a loss of bone and muscle mass, especially those bones and muscles normally used to support the body against gravity. Unlike the changes in the cardiovascular system, a direct correlation exists between the extent of bone and muscle mass loss and the time spent in microgravity. A more thorough understanding of the body's reactions to space—and how they can be managed—is important to maintain the health of ISS crews. Phase I research validated Skylab data indicating that astronauts continue to lose bone mass over the entire time spent in microgravity. Overall, the rate of bone mass loss is three to ten times greater than the rate of loss associated with aging on Earth. Muscles not used in microgravity experience a similar continual decline. Astronauts perform certain exercises to help minimize this loss, but Phase I research revealed that exercise is only partially effective. Investigators have found that if specific muscle groups are targeted during exercise, muscle strength can be protected in those areas. However, Phase I results showed that even with the current exercise program, integrated muscle func-



A Telemedicine Instrumentation Pack has been designed to collect medical audio, video, and electronic data from patients in space. The support components, including the flat panel liquid crystal display, remote video camera, light source, and power supply, provide a basic infrastructure for the medical instrumentation. Data capabilities include electrocardiogram, blood pressure, and blood oxygen saturation measurements. The pack was successfully flown on the January 1998 Phase I Shuttle flight to test telemedicine capabilities from space. Although the pack was designed for use in space, its primary application will be to enhance the delivery of health care in remote locations on Earth. Toward this end, NASA recently demonstrated the pack in Texas and Montana.

tion was not up to standard levels. This indicated that *Mir*'s exercise countermeasure regimen needs modification to help the ISS astronauts better deal with the effects of microgravity.

When coupled with changes in urinary output, the bone calcium loss experienced by astronauts could also increase the risk of developing kidney stones. Experiments were run on urine samples from Phase I astronauts and cosmonauts and compared to the results from more than 150 Space Shuttle astronauts. The findings suggest that an astronaut's risk of developing kidney stones is directly proportional to the time spent in space. Data from these experiments are being used to better understand exactly why the risk increases, helping medical personnel to design preventative treatments to minimize astronauts' susceptibility to kidney stone formation.

Without gravity's influence in space, an astronaut's nervous system must change the way it controls coordination and balance. Upon return to Earth, astronauts must readjust to the presence of gravity. Phase I research has shown that longer stays in space result in more significant changes in "neurosensory" functions (i.e., those that involve coordination between the brain and the senses). Examples of these neurosensory changes include less control over posture, the deterioration of eye-head coordination while moving, and difficulty fixing the eyes on a moving target. Balance difficulties are much more pronounced in long-term travelers than in Space Shuttle subjects. Knowledge gained from neurosensory work on *Mir* is helping us to develop better postflight recovery plans for ISS astronauts; the same work is also shedding light on the basic functioning of the nervous system itself, helping researchers here on Earth in a variety of medical disciplines.

After flight, a period of recovery is necessary to readjust to a gravity environment. The postflight care program begins even before crew members return to Earth; NASA found from Phase I experience that having long-duration crew members stay in a reclining position when returning to Earth seems to counter the effects of the sudden return of gravity. This position inhibits the abrupt redistribution of blood from the head and chest area normally associated with the return to gravity. All returning long-duration crew members now use a recumbent seat. Once on Earth, the time necessary to accomplish rehabilitation varies from individual to individual, but requires several weeks for the initial phase, and several months for fuller recovery. In dealing with returning Phase I crews, NASA learned that

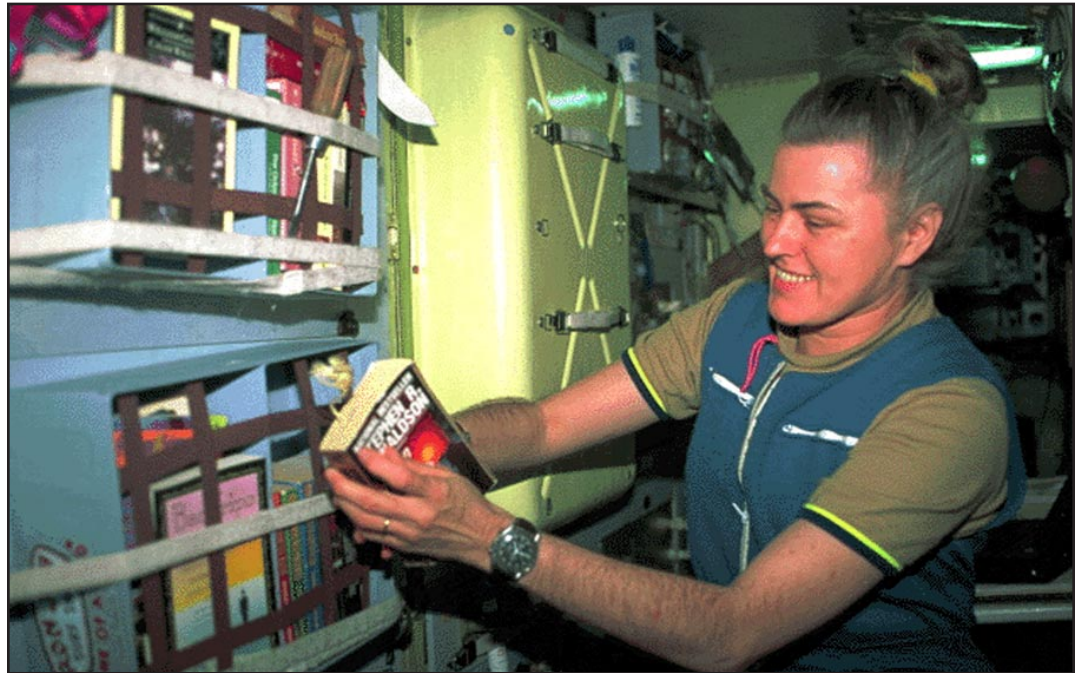
What day is it? Or is it even day? All Earth-bound creatures, especially humans, are accustomed to a 24-hour day-night cycle. Although we can adjust this cycle when moving from time zone to time zone (the "jet lag" phenomenon), it was much more complicated for *Mir* crew members; they interacted with two ground control centers with a 9-hour time difference and rendezvoused with spacecraft launched from both the Eastern and Western Hemispheres. *Mir* crew members had to shift their wake and sleep patterns to accommodate these launches, dockings, and communications. NASA is conducting research on various measures, including the use of melatonin, to ward off the physical stresses associated with this continual shifting.

continuous oversight during the rehabilitation period is important for a quick and full recovery.

Behavioral, psychosocial, and cross-cultural concerns have proven to be significant issues for long-duration missions. The Phase I experience reinforced the need for a customized program of psychological support for each ISS crew member. Family members were included in preflight psychological preparation and training for later Phase I missions. Also, preflight team building (between crew members and ground personnel), skills development, language and behavioral training, and mechanisms for adequate monitoring of performance and psychological issues were all essential to mission success. Adequate time for quality personal communications during missions is also critical.

Through Phase I, NASA gained practical experience in meeting the work and rest needs of astronauts on long-duration flights. Reasonable work schedules, rest periods, time off, entertainment and relaxation time, opportunities for social interaction, and regular communication with family and friends proved essential for both the flight crews and NASA personnel stationed in Russia. The onorbit laptop computer served as a way for crew members to have daily communications with their family members on Earth. NASA also noted that work “underload” can be just as bad as overload. Personal quarters for crew members on long-duration missions are important to ensure adequate sleep, privacy, and a place to maintain personal effects. These considerations are being incorporated into the ISS program.

Phase I also included important research that benefits the health of all humans. Researchers use data about the structure of key human proteins to design medications to treat or prevent illness. Certain protein crystals grown in space can be much larger and have fewer imperfections than their Earth-grown counterparts; for these reasons, some space-grown crystals are a promising asset for sophisticated drug design research. However, many proteins cannot be successfully crystallized in the relatively short time in space provided by the Shuttle. Through the Phase I program, we expanded the period of space protein crystal growth from just over 2 weeks to several months; in fact, NASA’s longest period of onorbit protein crystal growth was achieved on *Mir* (March to September 1996). Thousands of high-quality crystals have been produced and returned to Earth for analysis. For example, *Mir*-grown crystals enabled scientists to obtain an extremely accurate measurement of insulin’s structure. The structure of recombinant human insulin has



The Phase I program gave NASA experience in planning long-term missions; one of the lessons learned is that the psychological health of the crew depends on having a manageable workload and time for relaxation. Here, Dr. Shannon Lucid enjoys a book brought to the station in the payload capacity reserved for crew personal effects.

This protein crystal is the largest histone crystal grown to date, either on orbit or on the ground. Histones are proteins involved in the basic life processes of humans. Mir experiments have also produced the largest-ever crystals of the protein human antithrombin III. Although images are not yet ready for publication, early analysis of the protein indicates that it may have some application in the treatment of stroke victims.



also been determined with *Mir*-grown crystals. Perhaps most significantly, Phase I work validated a new method for growing certain crystals in space that is simpler, more effective, and much more productive than previous techniques. Researchers found that small protein samples yielded results as good as or better than the larger samples previously thought

necessary. This finding expanded the capacity for growing crystals to more than 30 times that of conventional space flight techniques, allowing a single apparatus to accommodate thousands of samples.

Microgravity has also proven to be a useful tool for growing high-quality tissue cultures. Ground-based tissue cultures often take on a flat, disk-like shape that fails to reflect how the tissue would behave inside the body. Without gravity, however, cellular cultures can form three-dimensional structures that more closely resemble true human tissue. Results from Phase I research are being used to refine an apparatus known as a bioreactor, a facility for growing three-dimensional tissues that on Earth mimics microgravity through the use of rotation. On *Mir*, researchers grew bovine cartilage for a record-breaking 4 months. Eventually, tissues cultured outside the human body in devices such as the bioreactor may be used in tissue transplants. Research into tissue engineering continued through the final increments of the Phase I program. Bone marrow and kidney cells were cultured in Increment 6; the final Phase I increment involved growing human breast cancer and blood vessel cells. These types of investigations could determine whether microgravity affords any advantage in inducing blood vessel formation in genetically engineered tissues (thus producing a “better” tissue sample overall).

NASA and ESA flew a collection of scientific experiments in the “Biorack” facility on Phase I Shuttle flights STS-76 (March 1996), STS-81 (January 1997), and STS-84 (May 1997). The ESA-built Biorack integrates several scientific facilities into a single biological research module. Shuttle crew members, including French astronaut Jean-Francois Clervoy on STS-84, ran experiments to study the effects of space flight on plant, fungus, tissue, and cell growth. Although the Biorack facility is not unique to the Phase I flights, its operations are viewed by the ISS partners as preparation for ISS research and life in space.

Using the Space Environment

Researchers used the Phase I opportunity to conduct research while validating ISS experimental approaches and equipment. Important questions have been asked in the fields of combustion science, fluid physics, materials science, gravitational biology, and Earth and space science (see Appendix A for these questions).

Fire behaves very differently in microgravity than on Earth, where gravity causes hot air to rise through a flame, creating the flickering, distorted shape typified by campfires. In

space, however, a candle flame forms a sphere around the center of combustion. Many secondary forces affecting fires can be studied in space but are impossible to observe on the ground, leading to a more thorough understanding of fire in general. A better understanding of the ways in which flames and smoke spread in space will help us control and prevent accidental fires. Preliminary Phase I results tell us that we cannot extrapolate results from ground-based experiments to space; the flow of air (oxygen) and fuel density are important variables that determine how long a fire lasts. Materials that burn on Earth may burn very slowly or not at all in microgravity. Adding a low-speed air flow past the material in question can increase the chance and rate of combustion. Work on *Mir* allowed us to verify that the hardware intended for ISS use is adequate for maintaining and controlling combustion experiments. This will allow researchers to refine their plans for use of the ISS.

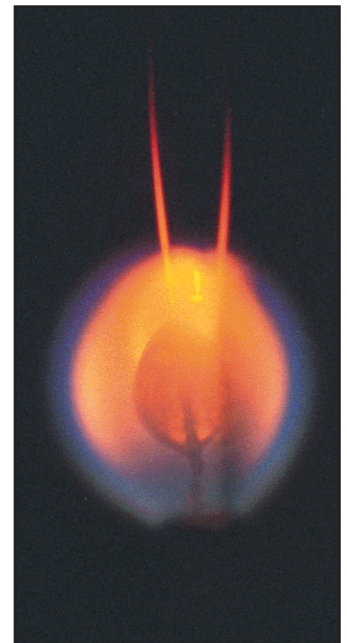
On Earth, gravity dominates the behavior of most fluids. In space, however, other forces—such as surface tension—control the shape, movement, and interaction of fluids. The way fluids behave is important in many space engineering problems, such as the flow of propellants, the movement of air inside the crew cabin, and the design of a life-support

In space, flames take on a spherical shape around the center of combustion. Here, air flow at the rate of 2 cm/s moves opposite the direction of flame spread. In the center of the flame a molten core of fuel is seen. On Earth, this fuel would have dripped away from the flame. In this Phase I experiment, however, the fuel stayed within the core of the fire until it was consumed.

When in space, we experience not the absence of gravity but the virtual absence of gravity's effects. Orbiting objects are actually still caught within Earth's gravitational field but are in a condition of continuous free-fall around Earth itself. A description of ourselves as "weightless" in the space environment is sometimes misleading. In an orbiting spacecraft, we float within the confines of the ship because we and the ship are falling at the same rate around the curve of the planet. We commonly refer to this state as microgravity, or weightlessness, because gravity's effects are barely felt.

Sometimes microgravity is a preferred environment in which to conduct experiments. Certain physical phenomena are difficult to observe on Earth because they are overshadowed by stronger, gravity-driven forces. Still other phenomena can be better understood in microgravity, where we can differentiate between gravity-dependent and nongravity-dependent processes.

When Sir Isaac Newton first articulated the theory of gravity in scientific terms, humankind was still bound to the surface of the planet. The past 40 years of space flight have allowed us, for the first time ever, to investigate phenomena in the virtual absence of gravity's effects. Gravity can no longer be treated as "scientific overhead"—always there, unavoidable, and invariable. This universal force of attraction between matter is now recognized and exploited aboard space stations as an invaluable scientific variable.



system to collect, clean, and dispense water. Fluid behavior also plays an important role in the functions of the human body. Phase I work has tested and verified fluid physics experiment hardware and the microgravity glovebox that will be used on the ISS. Phase I work has also indicated that our current models for the interaction of fluids in space are not as accurate as once thought. Researchers are now using Phase I data to refine these models in order to improve the efficiency of ISS hardware and fluids research.

Some solid granular materials can behave like fluids when subjected to certain stresses. Small amounts of liquid between grains cause the material to move in flow-like formations. Natural disasters such as landslides and earthquakes are good examples of the behavior of granular material (e.g., soil). Phase I research performed on the Space Shuttle allowed researchers to observe forces at work in granular materials that are normally masked by gravity's influence. The unique nature of the Phase I data should significantly advance the study of granular materials, helping researchers understand phenomena (such as landslides) that have direct impacts on our lives.

Two generations of the *Brassica rapa* plant, a member of the mustard family, were successfully grown on *Mir*. Seeds were planted, grown to maturity, pollinated, and harvested. These harvested seeds then underwent another complete life cycle aboard the Russian station. This first "seed-to-seed" cultivation of plants in space is a first step to self-sufficient food production for future space missions.



Phase I research has had a particular focus on developmental biology, in which plants and animals are studied for the effects of microgravity on their growth and reproduction. Phase I research determined that avian eggs could develop normally under space flight conditions. Experiments using Japanese quail eggs proved that early microgravity development of this species is possible. Long-duration missions may require the cultivation of crops for food, oxygen renewal, and crew morale. Both wheat and *Brassica rapa*, a mustard plant, were successfully grown on *Mir*. In fact, the mustard plant produced seeds, which were then planted and grown to maturity on the

Russian station. This marked the first "seed-to-seed" experiment in space.

Much of the space science work performed on *Mir* has served the dual purpose of reducing risks for the ISS while advancing our understanding of the solar system. Studies of the space radiation environment, for instance, have increased our basic understanding of cosmic and solar radiation while assuring us that existing ISS radiation protection is acceptable. Similarly, a cosmic dust collector, attached to the outside of *Mir* for 10 months, could provide information about the early solar system, helping us understand the evolution of the organic material from which life arose.

Research done on *Mir* to better understand the environment around the station also helps us better understand Earth. Phase I data showing that the South Atlantic Anomaly has moved since the 1970s shed light on the structure of Earth's magnetic field, which shapes the radiation belts. Since the magnetosphere protects our planet from solar and cosmic radiation, this knowledge can help researchers characterize the roles these factors play in Earth's environment.

The astronauts on *Mir* have added more than 19,000 images to the growing database (about 300,000 images) of Earth photographs from U.S. human space flights. Over the course of their long-duration missions, *Mir* crew members were able to observe and record long-term and seasonal changes such as agricultural and other land-use patterns, global deforestation, and the spread of droughts. In addition, astronauts observed and photographed rapidly occurring events such as volcanic eruptions and fires that otherwise may have gone undocumented.

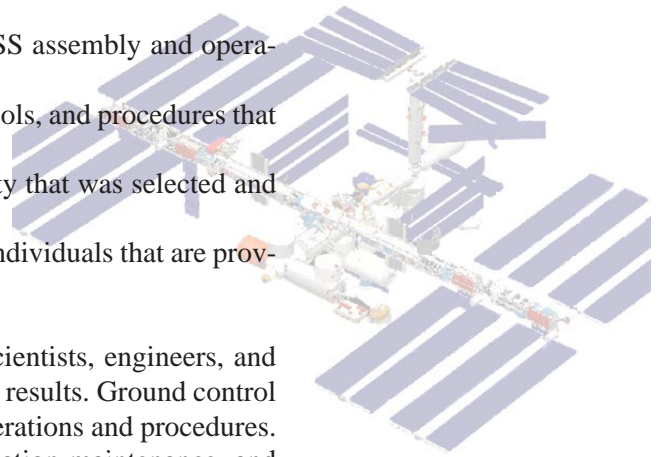


In April 1996, Mongolian forest fires raged out of control for more than 3 weeks. More than 80 fires consumed the land, and the smoke pall from the fires was described by the Mir crew members as the worst smoke they had ever seen from orbit. This view captures part of the thick smoke palls from the burning forests on the Mongolian steppe.

Part IV An Investment in Our Future

With the end of the Phase I program in June 1998, the United States completed a program that—in less than 5 years—simultaneously accomplished the following:

- Reduced the risks and increased the efficiency of planned ISS assembly and operations, both on the ground and on orbit;
- Led to re-evaluation and refinements in the equipment, protocols, and procedures that will be used to conduct scientific research on board the ISS;
- Resulted in successful, peer-reviewed research of high quality that was selected and approved by the scientific community; and
- Established working relationships among organizations and individuals that are proving invaluable for ISS development.



We continue to apply lessons from the Phase I experience. Scientists, engineers, and mission managers continue to compile data and to analyze research results. Ground control personnel continue to apply results based on Phase I findings to operations and procedures. NASA is still extracting critical information for flight logistics, station maintenance, and science operations. On the research side, even preliminary results from many Increment 7 investigations will not be known until several months after the final Phase I flight. For instance, analyses from water quality tests will help us assess the anticipated effectiveness of ISS water recycling and control plans. Analyses of the effects of radiation on a portable computer system will tell us if additional protective measures need to be built into the device. Many long-term experiments assessing the effects of space on certain materials were completed during Phase I; analyses will characterize the materials' responses to the ISS orbital environment. Still other investigations concluding in the last part of Phase I validated previous Phase I work by demonstrating that the results can be reproduced. Sustained U.S. involvement throughout Phase I has been critical in carrying the "lessons learned" forward to ease the transition from Phase I to Phase II of ISS development.

In 1998, we begin assembly of the most complex space structure in history. Forty-five American and Russian space flights later, a robust, fully operational space research laboratory will exist; this laboratory will continue its space operations for at least a decade. The Phase I program provided invaluable experience in space station operations, protocols, emergency procedures, and long-term research. The time spent on *Mir* allowed researchers to refine their equipment, procedures, and theories so that they can make the most of ISS capabilities. NASA will continue to analyze lessons learned from the Phase I experience long after the final Shuttle-*Mir* flight returns to Earth. Phases II and III of ISS development will be safer and more efficient because of Phase I efforts. Perhaps most importantly, the American and Russian space programs have come together in an unprecedented show of integration and teamwork. Phase I has been and continues to be an investment in our future.

The ISS is more than just the next step beyond *Mir*; it will provide almost four times the enclosed volume *Mir* did for research operations, having at least four outfitted laboratory modules, seven resident astronauts, and state-of-the-art instrumentation for scientific, technical, and commercial investigations.



Appendix A: Critical Research Questions for the Phase I Program

As the first phase in the ISS program, Shuttle-Mir research is considered part of the broader ISS agenda. A separate document, *The International Space Station: The NASA Research Plan, An Overview* (March 1998), includes a high-level set of research questions that the ISS program does and will address. The questions excerpted here represent those queries toward which Phase I research contributed. The questions are grouped in accordance with the NASA research disciplines.

Biomedical Research

- How does the space environment affect human physiology, and what additional health risks will occur with space flight?
- What are the long-term consequences for exposure to space radiation for humans?
- How does microgravity and the space environment affect human behavior and performance?

Space Medicine

- What are the effects of the microgravity environment on the utilization, route of administration, metabolism, elimination, and efficacy of medications?
- Can successful cardiopulmonary resuscitation and other methods of advanced cardiac life support be done in flight?
- What are the appropriate astronaut-selection criteria to ensure crew compatibility on long-duration missions, including those with international and multicultural crews?

Advanced Human Support

- How do life-support technology components interact with each other and with the crew over the long term in a closed microgravity environment?
- What tools and techniques are best suited for humans to use in microgravity during long-term space flight?
- How can we enhance human performance in space flight?

Gravitational Biology and Ecology

- How do living things sense and respond to gravity at the molecular, cellular, and genetic levels?

- What role does gravity play in the development of plants and animals?
- What are the long-term, including multigenerational, consequences of exposure to microgravity?

Biotechnology - Protein Crystal Growth

- What are the fundamental factors influencing protein crystal formation and growth, and which of these factors are responsible for increasing the quality of protein crystal growth in microgravity?
- How can the work done on protein crystal formation and growth in microgravity be extended to protein work on Earth?

Biotechnology - Cell Culture

- How can cell and tissue culturing be improved in microgravity, and how can we extend that to work here on Earth?
- What are the limits of cell-culturing in ground-based bioreactors, and are these limits exceeded in the microgravity environment?

Combustion Science

- What are the forces at work in combustion processes?

Fluid Physics

- How do solid-like to fluid-like transition behaviors in granular materials affect geo-mechanical applications (such as earthquakes and “quick” soil conditions)?

Materials Science

- How does a solid form from a liquid or vapor, and how is that formation influenced by impurities, free-liquid surfaces, and containers?
- What are the roles of transport phenomena in the generation of defects (flaws in materials ranging in size from microscopic to visible to the naked eye) as a material forms?

Earth Science

- What are the nature and extent of land-cover and land-use changes over time?

- How can we improve our oceanic and atmospheric modeling?

Space Science

- What are the chemical, organic, and isotopic compositions and distribution of particulate matter within the *Mir* orbit?

Commercial Product Development

- Will the growth of protein crystals, cell cultures, plants, and other biological materials in space lead to better products than can be produced on Earth?

Appendix B: Publications, Abstracts, and Presentations Resulting From Phase I Investigations as of March 1998

Journal Articles

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Rice BL, Lane HW. Dietary studies in the joint U.S.-Russian space program. *Journal of the American Dietetic Association* 97 (Suppl 2): S127–128, 1997.

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Desinov LV. Synchronous experiments at various altitudes: studies in the Precaspian region.

Evans C, Lulla KP, et al. Fluctuating water levels as indicators of change: examples from

around the world.

Evans CA, Lulla K, Glazovskii N, Desinov L. The NASA-Mir Earth Science Program: Global change detection from the Mir.

Evans CA, Robinson JA, Lulla KP, Wilkinson MJ. Fluctuating water levels as indicators of change: examples from around the world.

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Ignatov EI, Solovieva GD. Distinguishing characteristics of present-day coastal development of Southern Azerbaijan.

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Kravtsova VI. Coastal dynamics of the northeastern Caspian sea coast during transgression conditions.

Kravtsova VI, Myalo EG. Changes in vegetation in the coastal region of the Northern Caspian during sea level rise.

Layne CS, Mulavara AP, McDonald PV, Kozlovskaya IB, Pruett CJ, Bloomberg JJ. The effect of foot pressure on neuromuscular activation patterns generated during space flight. Submitted to the Journal of Neurophysiology, 1998.

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Robinson JA, McRay B. Twenty-eight years of urban growth in North America: combining remote sensing data from Apollo, Skylab and NASA-Mir.

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Appendix B: Publications, Abstracts, and Presentations Resulting From Phase I Investigations as of March 1998

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Svitoch AA, Bratanova ON. The use of aerospace data to analyze the geological structure of the northern coast of the Caspian Sea.

Varushchenko AN, Lukyanova SA, Solovieva GD. Present-day evolution of the Kara-Bogaz-Gol Gulf.

Wilkinson MJ. Aerosols as seen in the NASA/Mir handheld photography, 1994–1998.

Much of the Phase I research is ongoing. Specimen and data analyses will continue for several months. The Principal Investigators involved in Phase I are expected to publish findings in peer-reviewed publications approximately one year after they receive their specimens or data. At this time, over 30 journal articles are in review for publication. NASA plans to publish a compendium of Phase I results in the future.

**Published space biological research articles can be obtained free on the Internet at:
<http://www4.ncbi.nlm.nih.gov/PubMed/>**

**Or, for a fee on Spaceline at:
<http://spaceline.usuhs.mil/>**

**OLMSA ongoing research can be viewed at:
http://peer1.idi.usra.edu/peer_review/taskbook/taskbook.html**

Appendix C: Phase I Science Working Groups, Research Announcements, and Review Committees

A. *Mir* Science Working Group (Borer Committee), chaired by Jeffrey Borer, M.D., Cornell University.

1. “Recommendations of the *Mir* Science Working Group.” July 6, 1993
2. “Development of Recommendation for the Expansion of the Phase I Program.” January 8, 1994

B. Life Sciences Research Announcements (and associated peer review panels).

1. NASA Research Announcement 95-OLMSA-02, “Plant Space Research Utilizing U.S. Space Shuttle Middeck and Russian Space Station, *Mir*.” (1995)
2. NASA Research Announcement 94-OLMSA-01, “*Mir* Station (U.S. Flights) 1995-1997.” (1994)
3. NASA Research Announcement 94-OLMSA-03, “NASA/ESA Biorack Flight Opportunities.” (1994)
4. NASA Research Announcement 93-OLMSA-06, “Avian Developmental Biology Flight Experiments on *Mir*.” (1993)

Additional scientific peer review was also held to choose experiments to fly on the Shuttle/*Mir* Spacelab flight (Shuttle flight STS-71, *Mir* flight 18) on June 30, 1994.

C. Microgravity Sciences Research Announcements (and associated peer review panels).

1. NASA Research Announcement 95-OLMSA-03, “Microgravity Combustion Science: Research and Flight Experiment Opportunities.” (1995)
2. NASA Research Announcement 94-OLMSA-02 “Microgravity Biotechnology: Research and Flight Experiment Opportunities.” (1994)
3. NASA Research Announcement 94-OLMSA-05 “Microgravity NASA Fluid Physics: Research and Flight Experiment Opportunities.” (1994)
4. NASA Research Announcement 94-OLMSA-06 “Microgravity Materials Science: Research and Flight Experiment Opportunities.” (1994)
5. NASA Research Announcement 94-OLMSA-02, “Biotechnology: Research

and Flight Experiment Opportunities.” (1994)

6. NASA Research Announcement 94-OLMSA-05, “Microgravity Fluid Physics: Research and Flight Experiment Opportunities.” (1994)

7. NASA Research Announcement 94-OLMSA-06, “Microgravity Materials Science: Research and Flight Experiment Opportunities” (1994)

8. NASA Research Announcement 93-OLMSA-01, “Microgravity Combustion Science.” (1993)

D. Continuing Oversight Committees.

1. NASA-NIH Advisory Subcommittee on Biomedical and Behavioral Research

2. NASA Life and Microgravity Sciences and Applications Advisory Committee (and associated subcommittees)

This monograph was developed by the Office of Life and Microgravity Sciences and Applications (OLMSA) under the NASA Enterprise for the Human Exploration and Development of Space (HEDS). Assistance was provided by the Johnson Space Center’s Space and Life Sciences Directorate and the Phase I Program Office. For more information on OLMSA and HEDS programs, please visit their web site at

<http://www.osf.hq.nasa.gov/heds/>

For further information on the results of the Phase I program, please contact OLMSA at NASA Headquarters, 300 E Street, S.W., Washington, DC 20546-0001, phone (202) 358-0122. Also see the following web sites:

<http://titania.osf.hq.nasa.gov/mir/>
<http://shuttle-mir.nasa.gov/>

This document and others on the ISS Research Program can be found on the OLMSA homepage:

<http://www.hq.nasa.gov/office/olmsa/>